TECHNO-ECONOMIC ANALYSIS OF NETWORK CONFIGURATION OF PV-BASED OFF-GRID DISTRIBUTION SYSTEM

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ABSTRACT

Only 15% of rural population in Sub-Saharan Africa has access to electricity. The focus in this study is on design and techno-economic analysis of low voltage (LV) distribution network configuration relying on PV- and energy-storage-based off-grid solutions for African rural conditions. In the paper, three different grid design approaches are studied for three real existing Namibian villages. As a result, the most economically and technically feasible and cost effective off-grid system configurations are defined case by case.

INTRODUCTION

Only 43% of population has access to electricity in Sub-Saharan Africa countries. This percentage goes rapidly down if we are talking about rural areas (15%) [1]. Moreover, 89% of electricity is generated by coal-fired power stations [2], even Africa is one of the most favourable places for the implementation of solar photo-voltaics (PV) energy production. According to the "World Sunshine Map", it gets more sun days per year than any other continent in the world [3].

This paper consider Namibia as case study, a country in Sub-Saharan Africa, which has one of the highest solar radiation. Therefore, PV-battery-based off-grid system is one possible solution for electrification issue. Majority of the existing systems are either of two types: 1) solar house systems (SHS), of which power, typically, doesn't exceed 100 W, and supply is a separated consumer; or 2) solar charging systems (SCS), which can have power rating up to 15 kW and is aimed as a rule to phone charging [4]. However, these systems are not intended for uninterrupted power supply that meet the power quality requirements [5]. In order to guarantee such requirements, there is a need to design a common off-grid power system, to which each consumer is connected to, which is sourced by a PV power plant, and backed up by a battery energy storage system (BESS). Typically, off-grid systems consist of components mentioned above. Besides these, there are power electronics (converter/inverter) for voltage transformation and power lines for power delivery.

Proposed off-grid system design starts from sizing of the PV array. The descriptions of PV plant and sizing methodology are presented in [6]. In order to maximize PV plant output power, a maximum power point tracker (MPPT) is applied in all modern solar power systems. Characterization of the devices has been presented in [7]. Authors in [10] describe power electronic implementation for off-grid power system. Next step in off-grid system design is battery energy storage system (BESS). BESS provides energy and power in the absence of the sun, including the operation during the night time. Detailed description of the BESS dimensioning is presented in [8]. Based on parameters presented in [9], lithium-ion batteries are found feasible and chosen for the BESS of the concept.

Due to safe and efficiency issues, low voltage is chosen for proposed off-grids. There are three different power distribution network configurations compared in the paper:

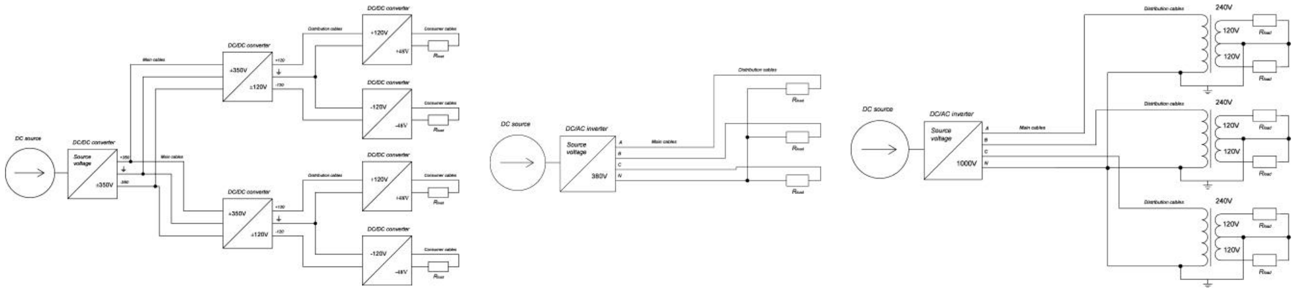
- DC distribution, which presupposes usage up to three voltage levels: main feeder line voltage, distribution network branch voltage (120-1500 VDC), and consumer premise network voltage (48 VDC) [11] (Figure 1a).
- AC European 230 VAC distribution [IEC 60038, IEC 50160, CEN-ELEC HD 472 S1], assuming one or three phase and up to two voltage levels: main feeder line and branches (Figure 1b).
- AC American 120 VAC distribution [ANSI C84.1-1989], implying two voltage levels: main feeder line with one or three phases and branch voltage level with split-phase configuration (Figure 1c).

The goal of the study is to determine the most cost-efficient configuration of the off-grid system. Three real existing Namibian villages, as cases, are considered in the paper. In addition, concept design includes such the key things as modularity, plug&play, scalability, and affordability. This allows interconnecting and scaling the off grids together in a long-term perspective.

OFF-GRID DESIGN METHODOLOGY

Research concept descriptions

The paper considers three different network configurations based on geographical analysis of customer premises in selected villages of regions in Namibia; dense rural grid, scattered rural grid and dense city grid. Within each topology, distribution network configuration, including different voltage levels, is considered: 1) bipolar low-voltage DC distribution with voltages from 48 to 1500 VDC, 2) European AC 230 VAC distribution and 3) American AC 120 VAC distribution. In addition to different topologies and configurations, rising load capacity of the consumers is assumed and considered in



(a) DC distribution (b) AC European 230 VAC distribution (c) AC American 120 VAC distribution

Fig. 1: Power distribution network configurations.

the analysis; this emulates development of infrastructure and consumer's need. The load capacity stages are named as "Tier", which is represented in [12]. There are five tiers: Tier 1; from 3 W (Minimum capacity) to 15 W (Accepted capacity); Tier 2; 50–100 W; Tier 3; 200–300 W, Tier 4; 800–1000 W, Tier 5; 2000–2200 W, respectively.

The aim of the paper is to define the most techno-economic efficient solution for an off-grid power system. Matlab is used in the computation of different topologies. The computation optimizes cable cross section, converter/ inverter/transformer nominal power ratings, distribution line type and voltage level based on minimization of total system costs. Moreover, costs of installation, maintenance, replacement, and losses are taken into account in the analysis. Parameters and costs of the system equipment are taken from [13]–[14]. System cost per kWh (€/kWh) at different stages of system development is estimated.

Cost calculation descriptions

The paper includes both technical and economic calculations. Common methodology is applied to all three configurations under study.

Distribution line costs calculation:

Distribution line costs calculation starts from identifying technical parameters of the cable, such as resistance, transmission capacity, and losses in transmission lines. Wire resistance, which is used in the calculations is:

$$R_{\text{cable}} = \frac{\rho_{\text{Cu}} \cdot L_{\text{cable}}}{S_{\text{line}}}, \tag{1}$$

where $\rho_{\text{Cu}}=0{,}17\,\frac{\Omega\times\text{mm}^2}{\text{m}}$ is a specific resistance of copper, L_{cable} [m] is a length of a line and S_{line} is a cross-section of a line. Line transmission capacity is determined:

$$S_{\text{load.capacity}} = K_{\text{config}} \cdot \frac{\mathrm{d}V_{\text{cable}} \cdot V^2}{R_{\text{cable}}}, \tag{2}$$

where $\mathrm{d}V_{\text{cable}}$ is the allowed voltage drop; for the intermediate DC grid point is 13%; for the end DC users is 3% [15]; and for AC users is 5% [16]. V is the nominal voltage. And K_{config} is coefficient of configuration; K_{config} = 1 for 1-phase AC; K_{config} = 2 for bipolar DC and split-phase AC; K_{config} = 3 for 3-phase AC configuration. Current through the distribution line is defined by:

$$I_{\text{cable}} = \frac{V_{\text{cable}}}{R_{\text{load}} \cdot K_{\text{config}} + R_{\text{cable}}}, \tag{3}$$

where V_{cable} [V] is nominal line voltage, $R_{\text{load}}[\Omega]$ is load resistance. Factual voltage drop can be defined:

$$V_{\text{cable.fact}} = I_{\text{cable}} \cdot R_{\text{cable}}. \tag{4}$$

Capacity losses in the line are calculated with:

$$S_{\text{TL.losses.W}} = K_{\text{config}} \cdot I_{\text{cable}} \cdot \mathrm{d}V_{\text{cable.fact}}. \tag{5}$$

Energy losses in line per day are:

$$S_{\text{TL.losses.Wh}} = S_{\text{TL.losses.W}} \cdot t_{\text{load}}, \tag{6}$$

where, t_{load} [h] is a load duration.

Next, material, installation and losses costs are calculated based on technical parameters and pricing.

Line material costs are calculated with:

$$C_{\text{TL.material}} = L_{\text{cable}} \cdot TL_{\text{price.material}}, \tag{7}$$

where $TL_{\text{price.material}}$ [€/m] is transmission line (TL) material price per unit. Line installation costs are:

$$C_{\text{TL.installation}} = L_{\text{cable}} \cdot TL_{\text{price.installation}}, \tag{8}$$

where $TL_{\text{price.installation}}$ [€/m] is installation price per unit (varies depending on cable cross section and number of cores) [17]. Costs of losses in transmission line for 20 years are:

$$C_{\text{TL.losses}} = S_{\text{TL.losses.Wh}} \cdot C_{\text{Energy.tariff}} \cdot 20 \cdot 365.2, \tag{9}$$

where $C_{\text{Energy.tariff}}=0.08$[€/kWh] is used as the estimated energy tariff [18].

Power electronic costs calculation:

Power electronic costs calculation starts from defining the total number of power electronic units and ends with material and replacement cost calculation. Number of power electronic equipment is calculated with:

$$N_{\text{PE}} = \frac{P_{\text{load}}}{P_{\text{PE}}}, \tag{10}$$

where P_{PE} [W] is nominal power of power electronic unit, P_{load} [W] is a total load capacity. Power electronic material and installation costs are estimated:

$$C_{\text{PE.material.installation}} = PE_{\text{price}} \cdot N_{\text{PE}}, \tag{11}$$

where PE_{price} [€/unit] price including material and installation of power electronic equipment. Power electronic replacement costs are calculated with:

$$C_{\text{PE.replacement}} = k_{\text{price.dec}} \cdot \left(\frac{20}{t_{\text{PE}}} - 1 \right) \cdot PE_{\text{price}} \cdot N_{\text{PE}}, \qquad (12)$$

where $k_{\text{price.dec}} = 0.93$ is a coefficient assuming price reduction for 20 years, $t_{\text{PE}} = 10$ [years] is power electronic operation period [19], [20]. Costs of losses in power electronic equipment for 20 years are estimated with:

$$C_{\text{TL.losses}} = P_{\text{load}} \cdot (1 - \eta_{\text{PE}}) \cdot t_{\text{load}} \cdot C_{\text{Energy.tariff}} \cdot 20 \cdot 365.2. \qquad (13)$$

PV plant and energy storage costs calculation:
PV and ES costs are calculated as power electronic ones, and differ only in calculation of required power. Required power for PV power plant is:

$$P_{\text{PV}} = \frac{P_{\text{load}} \cdot K_{\text{sun.p.h.}}}{\eta_{\text{PE}} \cdot K_{\text{sun.p.h.}}} + \frac{P_{\text{load}} \cdot (24 - K_{\text{sun.p.h.}})}{\eta_{\text{PE}} \cdot \eta_{\text{ES}} \cdot K_{\text{sun.p.h.}}}, \qquad (14)$$

where η_{PE} is efficiency of power electronic converter, η_{ES} is round-trip efficiency of batteries, $K_{\text{sun.p.h.}}$ in kWh/m^2/day is solar insolation for PV power plant location for the worst month in a year. Required capacity for ES [Ah] is calculated with:

$$E_{\text{ES}} = \frac{2 \cdot t_{\text{load}} \cdot P_{\text{load}}}{\eta_{\text{PE}} \cdot \eta_{\text{ES}} \cdot K_{\text{dis.}} \cdot V_{\text{ES}}}, \qquad (15)$$

where $K_{\text{dis.}}$ is a coefficient of possible depth of discharge, and V_{ES} is a voltage rating of battery string.

Produced energy price calculation:
Analysis of different topologies with various load sizes, based on the total costs is complicated. The price of energy per kWh is more relevant comparison criteria because it assumes not only the costs, but also the amount of produced energy. Energy produced for 20 years by PV plant is:

$$E_{\text{PV.20.y.}} = 20 \cdot 365.2 \cdot N_{\text{PV}} \cdot P_{\text{PV}} \cdot \frac{K_{\text{sun.p.h.}}^{\max} + K_{\text{sun.p.h.}}^{\min}}{2} \cdot \eta_{\text{ES}} \cdot \eta_{\text{PE}}. \qquad (16)$$

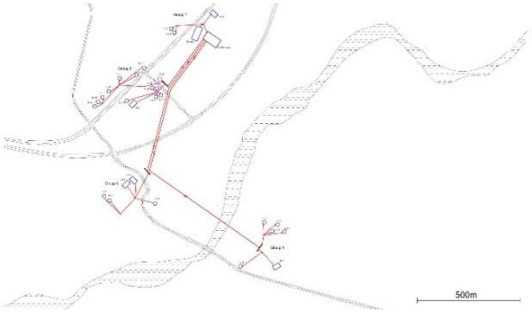
Price per kWh produced energy is:

$$C_{\text{per/kWh}} = \frac{C_{\text{system.total}}}{E_{\text{PV.20.y}}}, \qquad (17)$$

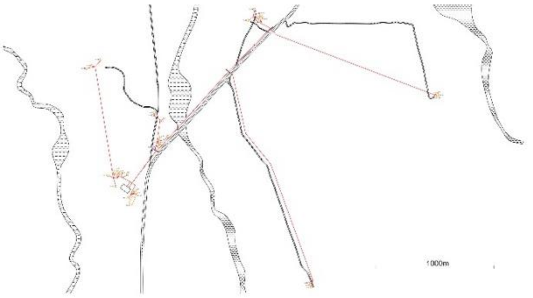
where $C_{\text{system.total}}$ [€] is the sum of transmission line, power electronic, PV array, ES and system installation costs.

CASE STUDY

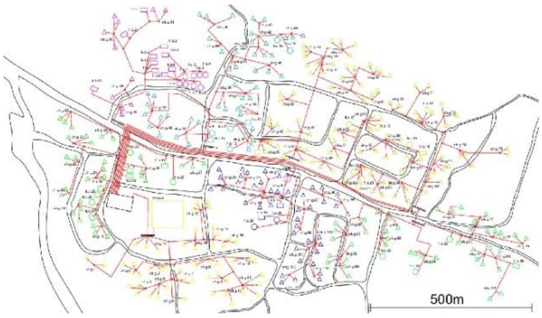
Techno-economic analysis of network configurations applied to different real existing villages is conducted. The villages are chosen in such a way that each of them has its own features, such as concentration of houses per unit area, and the number and location of the consumers. The PV power plant is located near building indicated as a school. School's power demand is estimated as 2 kW, which includes lighting (3 W/m^2), cooling/heating system (1 kW), water pumping (480 W) and electric devices; TV (40 W), computer (70 W), phone (2 W). Inclusion of the school in the design consideration allows involving social and government side investment and putting generation near the biggest capacity consumer. Based on location and capacity, all consumers are divided into groups. Each group, depending on configuration is divided into two or three subgroups, which is needed for balance provision in bipolar DC, and split-phase and 3-phase AC systems. A main feeder line (heavy lines in Figure 2) connects power generation with a group distribution point. Within one distribution group, fine lines are applied.



(a) Dense rural grid.



(b) Scattered rural grid.



(c) Dense city grid.

Fig. 2: Case study topologies.

A. Case 1: Dense rural grid

Figure 2a depicts real Namibian village Omitara, which is found using satellite Google map, and located in the –22.29, 18.00 of magnitude coordinates. Consumer's location in the village is relatively concentrated. There are 28 houses and a school. It is divided into four groups in different distances from power source. The PV plant and

BESS are located near the first group, to the next there is also the assumed school.

B. Case 2: Scattered rural grid

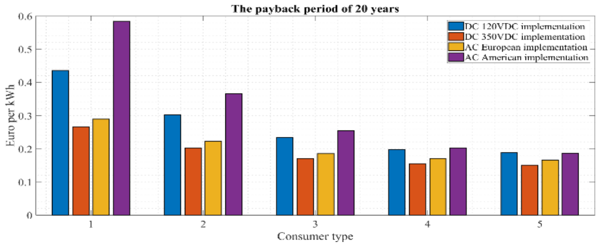
Figure 2b illustrates another real Namibian village. It is located in the –19.394431, 13.877596 of magnitude coordinates. The main feature of this case is that there are small groups of houses in a long distance from each other. The length among separate groups is 1.5 kilometers in average value. There are 32 houses, which are shared in two groups. In such system topology formation of the group and definition of the direction of the power lines is rather challenging. School, PV plant and BESS location is selected near the biggest cluster of houses.

C. Case 3: Dense city grid

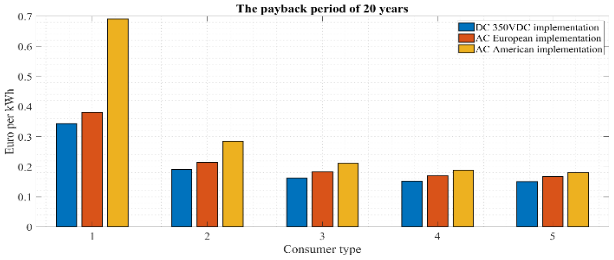
Figure 2c shows one of the Windhoek outskirts located in the –22.501395, 17.008289 of magnitude coordinates. Distinctive characteristic of this case is the plenty of houses located on the territory of a small area, consequently highly branched network. The distance among buildings doesn't exceed hundred meters. Another feature of this case is the introduction of the shack group (sh.g.) as a load unit. It is a group of consumers with the sum load capacity equal to the house load unit. User voltage level 48 VDC in DC approach is used within shack group; in AC approaches, 220 VAC and 120 VAC is applied. Inner sh.g. wiring isn't considered due to minor impact on total cost. Estimated cable cross section is 6 mm^2 and 75 meters is a line distance limitation chosen for the shack group. The total number of load units is 51 houses and 103 shack groups. All buildings are divided into eight groups. One of the big houses on the map is assumed to be the school.

RESULTS

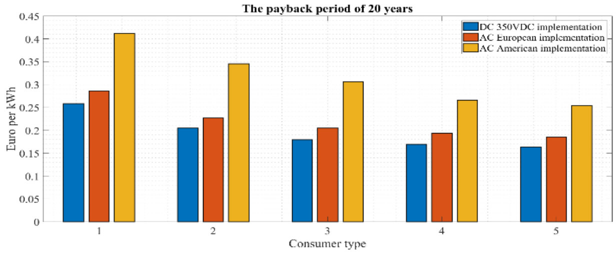
Within each topology, the most economically effective configuration is chosen based on the minimization of the system costs. Figure 3 depicts the energy tariff of different cases implementing various configuration. Within Dense rural case three and two voltage level bipolar DC configuration are compared. From the fist bar plot of Figure 3 it is seen that bipolar DC configuration with three voltage levels (350 VDC, 120 VDC and 48 VDC) is economically less effective. Consequently, it is not considered in further cases.



(a) Dense rural grid.



(b) Scattered rural grid.



(c) Dense city grid.

Fig. 3: Price per kWh in the studied cases.

From technical point of view, all grid design approaches can be applied for the studied cases. However, American AC one is the least cost-effective for all three cases. Energy production price of system with such configuration is significantly higher in all stages of the off-grid development by the reason of intermediate voltage transforming equipment. Bipolar DC and European AC configuration are relatively competitive. However, there is a difference in distribution network costs between bipolar DC and European AC grid design approaches in all tier stages of system development. In the grids with Tier 1 and 2 load sizes, network configuration has mainly influence on the price distinction; DC approach distribution network cost is less than European AC one. In addition to network costs, implementation of bipolar DC configuration requires DC/DC converters, while in European AC inverters, for solar PVs are used. Considered DC/DC converter price is lower but its efficiency is 1% higher than that of inverter, which influences on PV plant and battery storage size significantly only on last stages of system development (Tier 5). Ultimately, system costs per kWh in DC configuration is slightly lower in all stages of the system development. This is because of the higher transmission capacity of distribution network with bipolar DC configuration, higher power electronic efficiency and lower converter price.

Interconnection of off-grid systems is an issue that should also be elaborated in off-grid system design. For interconnection the considered off-grid DC approach with Namibian utility grid there is a need of additional grid converter installation. Accordingly, for the AC approach systems, transformers are required. If system voltages are different, combining several off-grids in bigger one could be applied with converters and inverters/transformers for DC and AC configurations, respectively. The energy tariff in Windhoek is 0.08 €/kWh. However, it is important to mention that this price couldn't be compared with energy production costs of designed off-grid system because first of all, the price of rural energy production is significantly higher than in a city.

CONCLUSIONS

According to conducted calculation in this paper, DC approach is the most cost effective solution for all grid topologies. However, assuming that prices of equipment could vary in real condition and due to small price difference between DC and European AC systems, either one can be considered as competitive. Despite this fact, implementation of DC grid configuration is more preferable because of additional advantages: implementation of 48 VDC end-consumer voltage is one more pro for DC approach; in poor engineering conditions, issue of electric safety is essential, and integration of extra low voltage decrease electric shock danger in comparison with 230 VAC. Another advantage is a possibility to dynamically increase low-voltage DC level of distribution lines thereby rising its transmission capacity. This feature (staying in low voltage region) allows to apply the same LV power lines and neglect the need for replacement of those while load demands are increased. However, bipolar DC configuration also has disadvantage: there are not that much consumer appliances available for 48 VDC.

Based on above-mentioned factors, it is possible to conclude that bipolar DC approach is economically and technically more efficient especially for the rural off-grids, while in dense city grid topology bipolar DC and European AC configuration could be considered as competitive.

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